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Pilossof

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(54) **ASYMMETRICAL DEFORMABLE
DIFFRACTIVE GRATING MODULATOR**

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patent is extended or adjusted under 35
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This patent is subject to a terminal dis-
claimer.

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G02B 26/02 (2006.01)

G02B 5/18 (2006.01)

(52) **U.S. Cl.**

CPC **G02B 26/00** (2013.01)

USPC **359/291**; 359/290; 359/295; 359/230;
359/231; 359/572; 359/559

(58) **Field of Classification Search**

USPC 359/290–295, 298, 230, 279, 558, 559,
359/572, 573, 850; 347/239; 438/65;
348/E5.142

See application file for complete search history.

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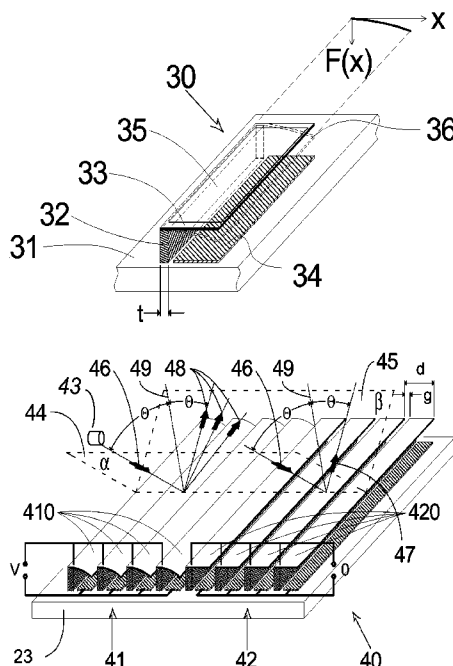
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(57) **ABSTRACT**

A method for modulating light using a micro-electro-me-
chanical structure includes providing a plurality of deform-
able mirror elements (30) having an L-shaped cross section.
Each of the deformable mirror elements is comprised of a
pedestal (32) and an elongated ribbon (33). Each of the rib-
bons has a reflective surface (35). A beam of light is directed
on the deformable mirror elements. The deformable mirror
elements is flexed about an axis parallel to a long dimension
of the ribbons to vary a curvature of at least one of the
reflective ribbons.

12 Claims, 6 Drawing Sheets



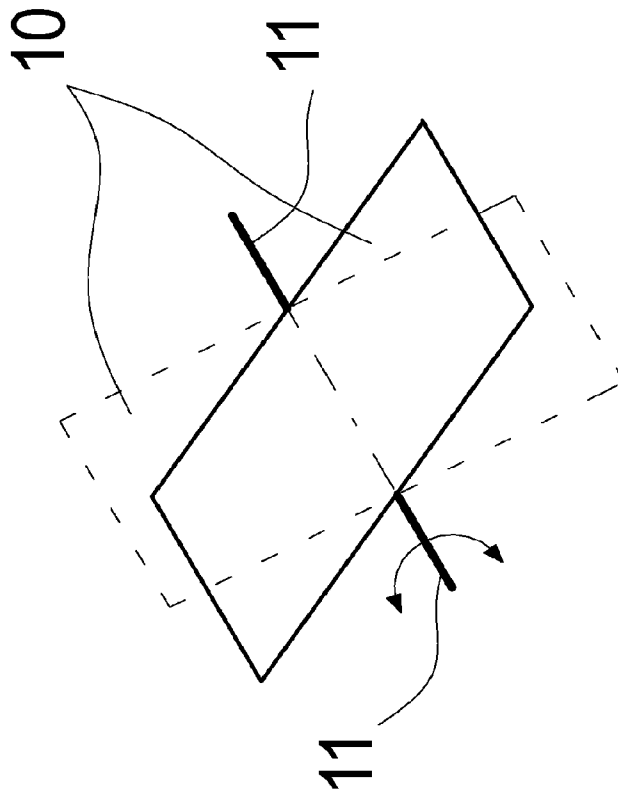


FIG. 1 (Prior art)

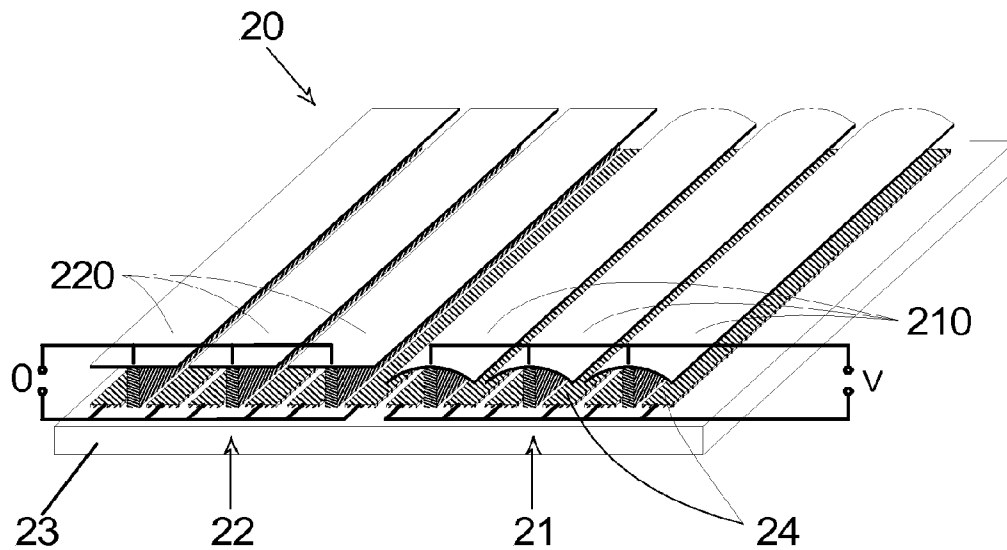


FIG. 2a
PRIOR ART

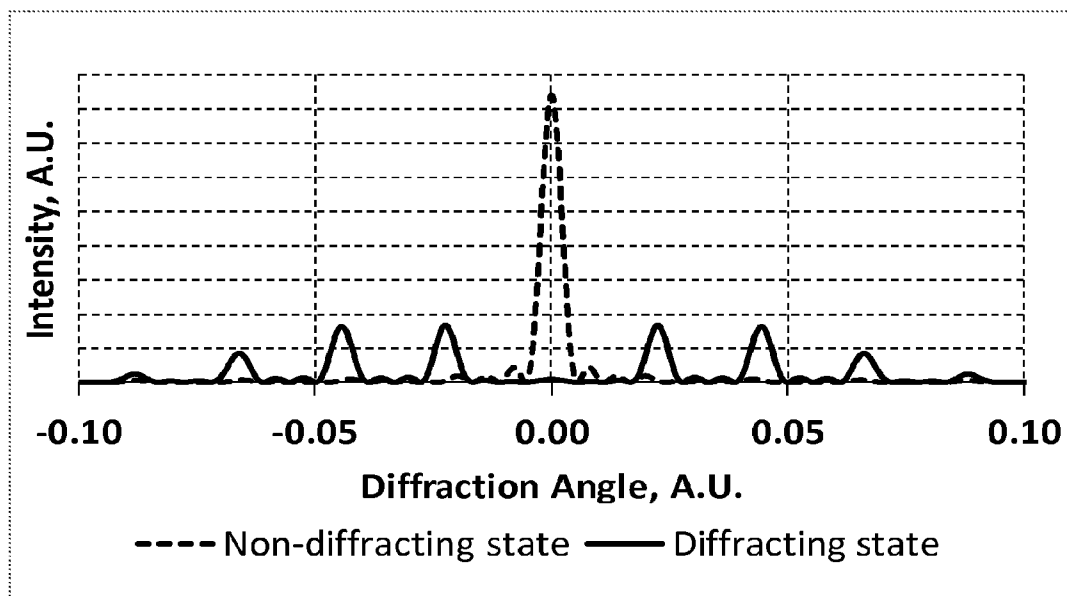


FIG. 2b

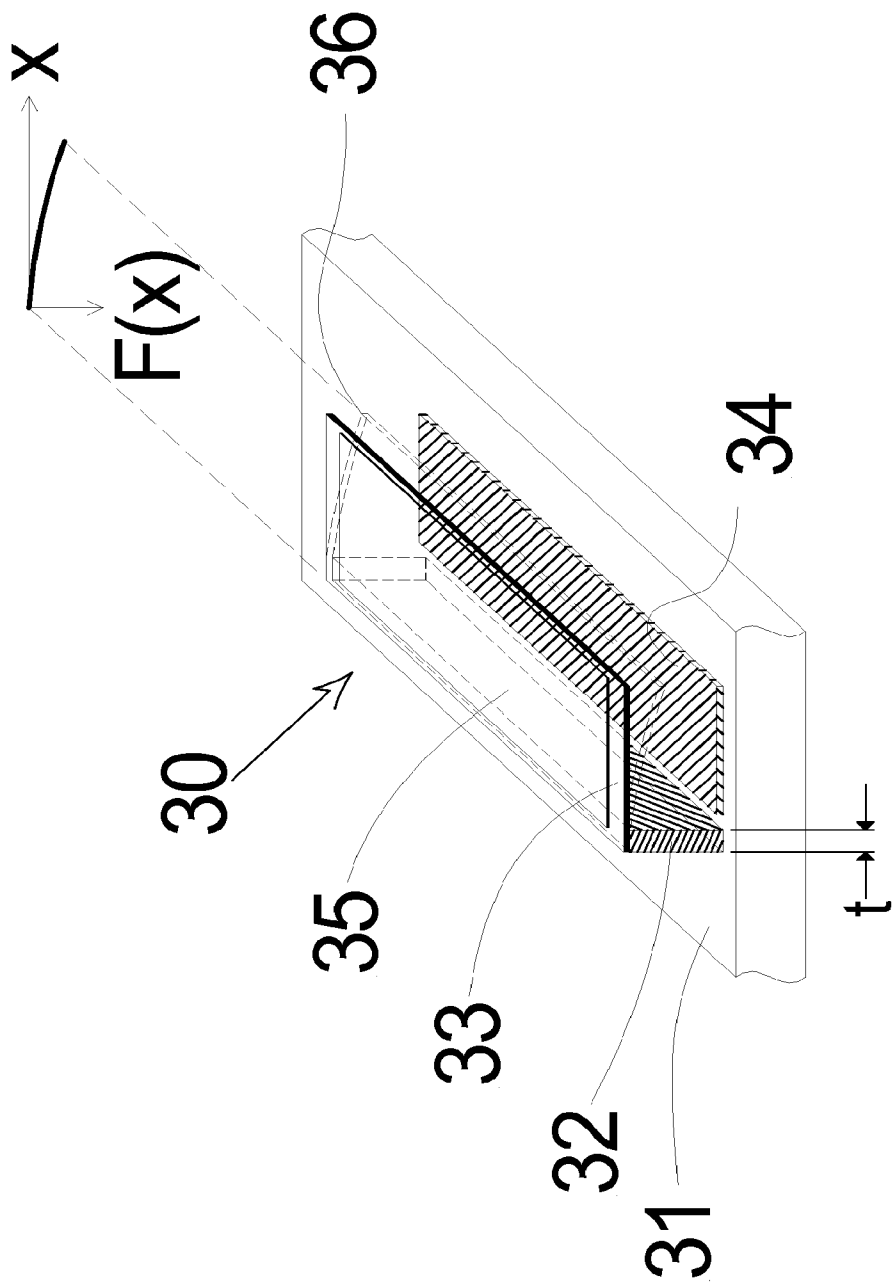


FIG. 3

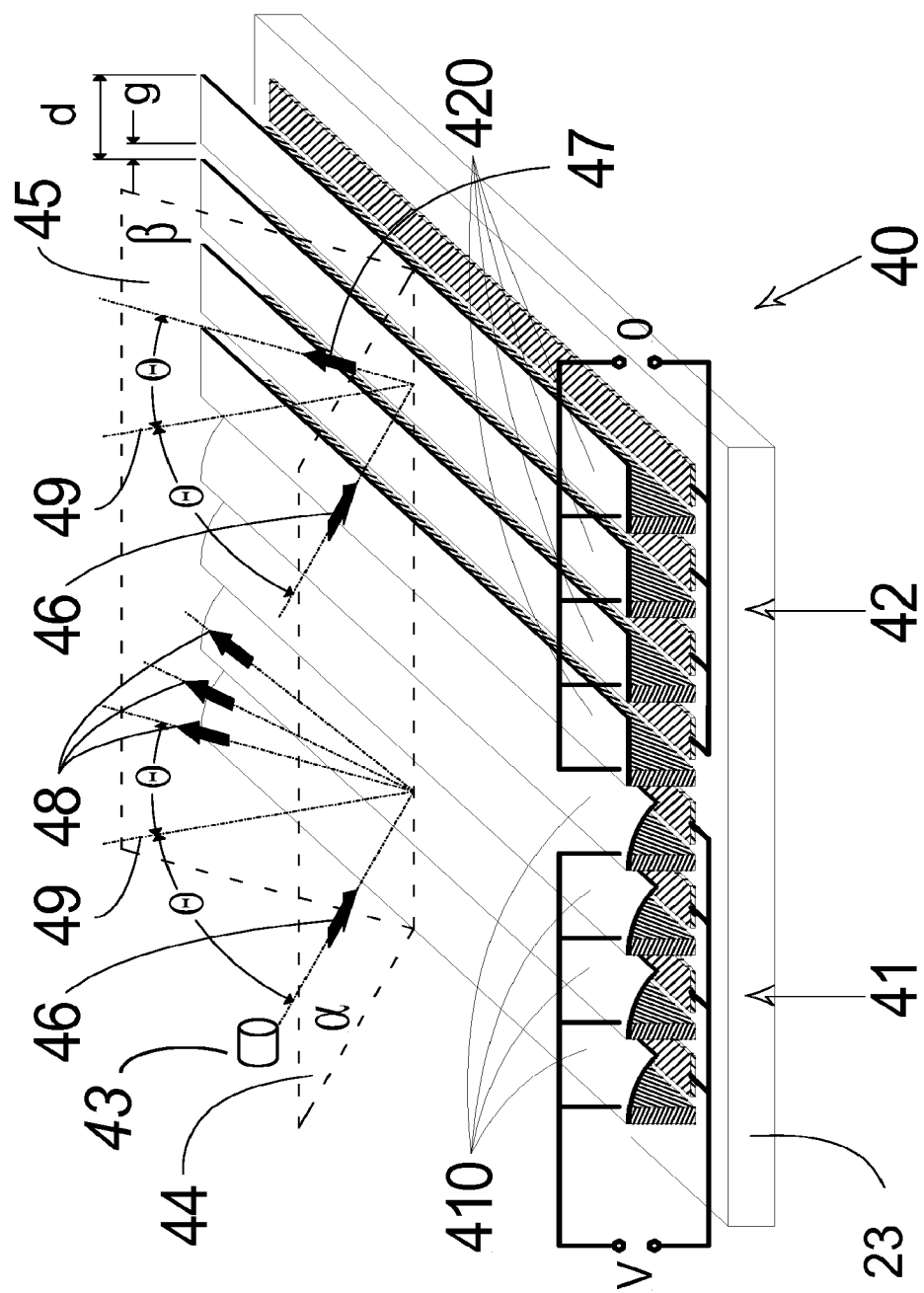


FIG. 4

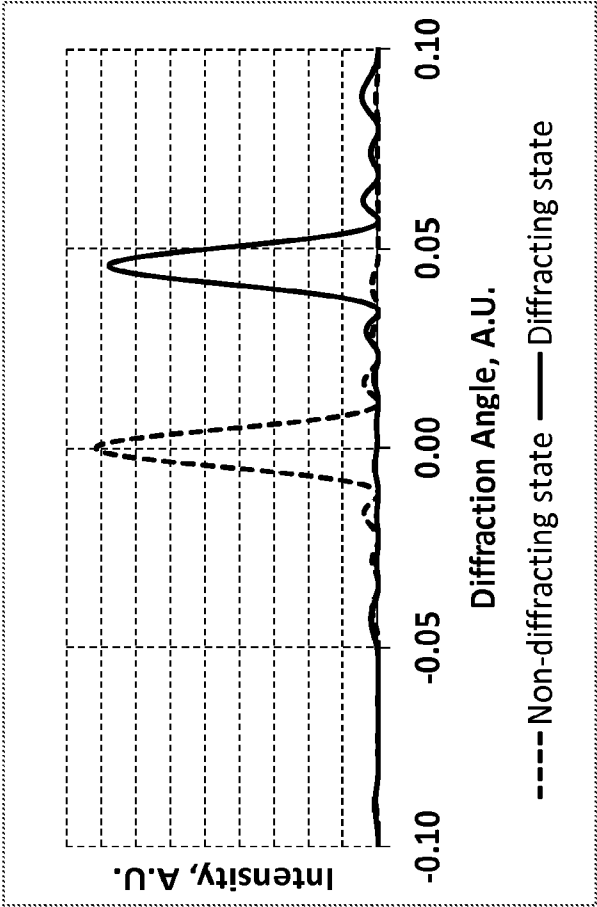


FIG. 5

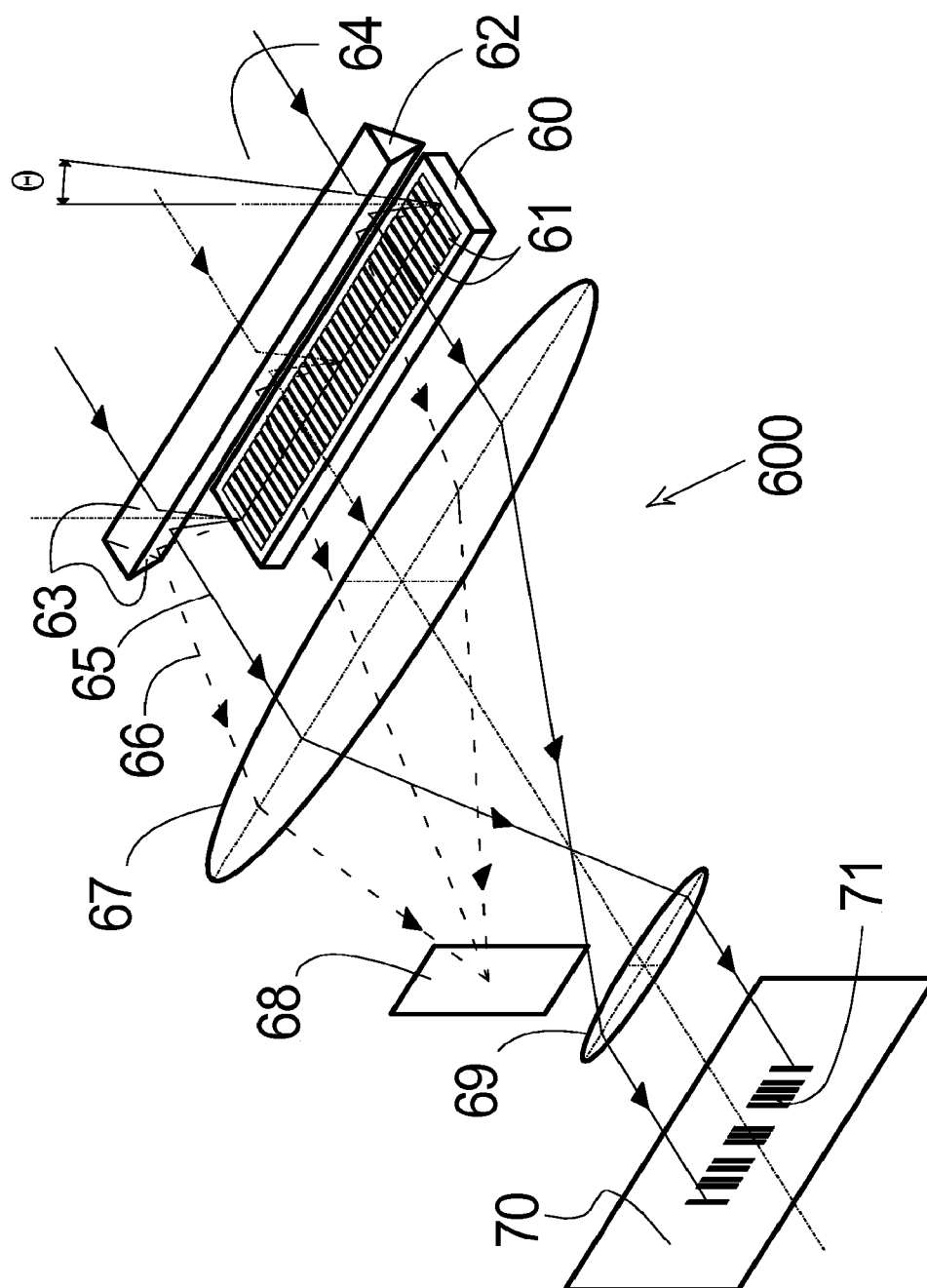


FIG. 6

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ASYMMETRICAL DEFORMABLE DIFFRACTIVE GRATING MODULATOR

CROSS REFERENCE TO RELATED APPLICATIONS

Reference is made to commonly-assigned copending U.S. patent application Ser. No. 13/737,983, filed Jan. 10, 2013, entitled ASYMMETRICAL DEFORMABLE DIFFRACTIVE GRATING MODULATOR; by Nissim Pilosoff; the disclosure of which is incorporated herein.

FIELD OF THE INVENTION

The present invention relates in general to micro-mechanical structures and in particular to diffractive grating modulators.

BACKGROUND OF THE INVENTION

Micro-electro-mechanical systems (MEMS) are used in many devices which require modulation of light. For example, projectors may use a digital micromirror device (DMD), which has thousands of micromirrors. A cantilever or hinged mirror **10** of this type, shown in FIG. 1, rotates on an axis **11** reflect a beam of light when in an on position. A disadvantage of this type of device is the relatively slow response time, $\sim 10 \mu\text{s}$, due to the low natural frequency of each single hinged mirror.

In another type of modulation device, the deformable diffractive grating light modulation systems, the diffractive element is formed as a long narrow ribbon. In one design, the ribbon bends along the long axis of the ribbon thus forming a "piston" type switching diffractive element. Typical piston type diffractive elements are shown in U.S. Pat. Nos. 5,311,360; 5,459,610; and 5,677,783.

In another design, shown in FIG. 2a, the cross section of the diffractive ribbon is T-shaped and the ribbon bends along its short axis. FIG. 2a illustrates two pixel elements **21** and **22** of a spatial light modulator (SLM) **20** built on a silicon substrate **23**, with each pixel comprised of three diffractive elements **210** and **220** respectfully. The pixels are driven using electrodes **24**. Pixel **21** is shown in energized state while pixel **22** is in a non-energized state. Resulting diffraction distribution of the two pixels is shown on FIG. 2b. In energized (diffracting) state, a pixel produces symmetrical angular distribution of light intensity consisting of many diffraction maximums. T-shaped ribbon types of diffractive elements are shown, for example, in U.S. Pat. Nos. 6,661,561; 6,836,352; and 6,856,448.

Both types of diffractive elements have some advantages, while suffering from some drawbacks. In both types, however, the width of one ribbon, the pitch, determines the grating period d , and the diffracted light is distributed within multiple diffractive orders symmetrically in both directions. See FIG. 2b. The diffraction efficiency of a single element is very low with typical contrast of about 50%. Therefore, in optical systems using deformable ribbons light modulators, more than one ribbon is used for forming an optical pixel, rendering the minimum optical pixel size to two times the grating period or $2d$.

SUMMARY OF THE INVENTION

Briefly, according to one aspect of the present invention a method for modulating light using a micro-electro-mechanical structure includes providing a plurality of deformable

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mirror elements having an L-shaped cross section. Each of the deformable mirror elements is comprised of a pedestal and an elongated ribbon. Each of the ribbons has a reflective surface. A beam of light is directed on the deformable mirror elements. The deformable mirror elements are flexed about an axis parallel to a long dimension of the ribbons to vary a curvature of at least one of the reflective ribbons.

The invention and its objects and advantages will become more apparent in the detailed description of the preferred embodiment presented below.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a prior art cantilever mirror.

FIGS. 2a and 2b show a prior art SLM based on T-shaped ribbons and corresponding angular distribution of light intensity.

FIG. 3 shows an L-shaped ribbon according to the present invention.

FIG. 4 is a cross-sectional view of a plurality of diffractive elements according to the present invention.

FIG. 5 shows intensity versus diffraction for L-shaped ribbons based SLM according to the present invention.

FIG. 6 is a schematic view of an optical system according to the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will be directed in particular to elements forming part of, or in cooperation more directly with the apparatus in accordance with the present invention. It is to be understood that elements not specifically shown or described may take various forms well known to those skilled in the art.

One embodiment of the present invention is a diffractive grating consisting of mirrors shaped as ribbons with asymmetrical cross-section as shown in FIG. 3. The single diffractive element **30** will have approximately the same diffraction efficiency as symmetrical ribbons, but at half the pitch value, allowing for two times higher system resolution, all other optical conditions being equal. Fabrication methods for deformable mirrors is not within the scope of the present invention, but it is well known and described in details in U.S. Pat. Nos. 5,311,360 and 5,661,592 and can be adapted to fabrication of the mirrors of the present invention.

Referring again to FIG. 3, the deformable mirror element **30** is fabricated for example on a silicon substrate **31**. A deformable mirror element **30** is comprised of a pedestal **32** which supports elongated ribbon **33**. Either the pedestal **32** or the ribbon **33** or both are made electrically insulating material. The ribbon **33** has an unsupported elongated portion laterally extending along the pedestal **32**. The surface of the ribbon **33** is coated with a highly reflective layer forming a mirror surface **35**. For clarity the mirror is shown smaller than the ribbon width, but it is appreciated that it should cover whole width of the ribbon.

The choice of the coating material depends on the wavelength of light the SLM is intended to work with. For example SLM intended to work with visible light may be coated with aluminum while SLM intended to work with near infrared light may be coated with gold. In an embodiment wherein the ribbon is made of electrically insulating material like silicon nitride and the reflective coating is not electrically conductive, a special conductive coating beneath the reflective coating should be considered. Thus, in FIG. 3 element **35** represents an electrical electrode and reflective coating at the same time.

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A second electrode **34** is formed on the surface of the substrate. Applying voltage between electrodes **34** and **35** energizes the ribbon and due to electrostatic forces, it bends along its shorter axis assuming position **36**. When the ribbon is bent, its surface profile in the shorter direction (X-direction in FIG. **3**) follows a profile function $F(x)$. $F(x)$ is taken into account when calculating the light intensity versus angle in diffracting state and depends on the dimensions of the ribbon, the mechanical properties of the material it builds from, and the applied voltage. Methods of calculating $F(x)$ and the intensity angular distribution in diffracting state are well known in the art. Generally, the closer $F(x)$ is to a straight line, the higher contrast ratio the SLM can achieve. Therefore it is desirable to have the thickness t of the post **32** as small as possible.

It is appreciated that the above discussed way of selecting and energizing a ribbon by means of electrostatic forces is only exemplary. Other methods like magnetic, thermal, etc. can also be used.

Reference is now made to FIG. **4** which shows a portion of SLM **40** with L-shaped deformable ribbons. The number of ribbons in a SLM can be hundreds or even thousands. The distance d between the ribbons is called the grating constant and determines the diffracting power of the device, while the ratio d/g , wherein g is the gap between the ribbons, is called the fill factor and affects the overall efficiency of the device. The higher the fill factor, the higher the device efficiency.

It is well known in the art that the diffraction efficiency depends on the number of individual elements contributing to the process. If a single pixel is formed from only one diffracting element the maximum achievable contrast is about 50%, which is not enough for most applications. Therefore individual pixels are usually formed from two or more diffracting elements. It is appreciated that the simultaneous wiring of four ribbons illustrated in FIG. **4** is only exemplary. The SLM can be built by pre-wiring groups of ribbons to form a pixel (as illustrated in FIG. **4**) or by wiring each individual ribbon and later forming pixels by simultaneous addressing of adjacent ribbons by the SLM driving electronics.

For simplicity, FIG. **4** illustrates only two pixel elements **41** and **42** and each pixel element consists of four ribbons (diffracting elements) **410** and **420** respectfully. Pixel **41** is in diffracting state and pixel **42** is in non-diffracting state. The incident light beam **46** from light source **43** lies in a plane at incidence angle α **44** and strikes the SLM plane at angle Θ relative to its normal **49**. The light falling at the non-energized (inactive) pixel element **42** will experience a simple reflection **47** and will propagate in the plane of reflection β **45** at angle Θ relative to the SLM **40** plane normal **49**. Light falling on the energized (active) pixel after reflection will propagate in different directions **48** governed by the laws of diffraction. Different directions of propagations constitute different diffraction orders as only one order, called "Zero order," will propagate in the plane of reflection **45** at angle Θ relative to the SLM **40** plane normal **49**, i.e. will obey the law of simple reflection. All other orders first, second, etc. will generally propagate in different planes and at different angles relative to the plane normal **49**.

For specific profile function $F(x)$ the angle of incidence Θ can be chosen in a way that the light propagating in Zero order direction is minimized and the diffracted light is concentrated predominantly in one of the higher diffracting orders first, second, etc. FIG. **5** illustrates such optimized angular distribution of light for pixels in diffracting and non-diffracting states. It can be seen that the diffracted light is concentrated predominantly in one diffraction maximum at one side of the grating, i.e. the grating is "blazed." This "blazing" property of

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the grating means that the diffracted light will be with approximately the same brightness as the non-diffracted.

The angular modulation of the light achieved by the SLM can be converted into spatial modulation. This is explained with the help of FIG. **6**. In an exemplary optical system **600**, a SLM **60** with pixel elements built and arranged as described above and shown in FIGS. **3-5** is illuminated with beam of light **64** using a prism **62** with two reflective surfaces **63**. It is appreciated that instead of a prism, a system of mirrors and direct illumination can be used. The illumination angle Θ is the same angle discussed above. After reflecting from the SLM, the light propagates within two beams **65** and **66**. Beam **65** originates from non-energized pixels while beam **66** originates from energized pictures. Element **61** is a diffractive element.

Beams **65** and **66** pass through lens **67** the focal plane (the system's Fourier plane) contains a blocker **68** which stops the light from beam **66**. After the blocker **68**, only light from non-energized pixel element will propagate through the rest of the optical system, i.e. only the Zero diffraction order will be allowed.

The next element downstream is lens or group of lenses **69** which together with lens **67** constitute an imaging system with object plane the SLM and image plane **70**, i.e. the SLM and plane **70** are conjugate. As all light from energized pixels will be stopped at the blocker **68** and the image **71** will contain only images of non-energized pixels. It is appreciated that it is possible to place the blocker **68** in such a way that it will stop the Zero Order and allow the higher diffractive orders. In such case the image plane will contain images of all energized pixels.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the scope of the invention.

PARTS LIST

10 hinged mirror
11 axis
20 spatial light modulator (SLM)
21 pixel element
22 pixel element
23 substrate
24 electrode
30 deformable mirror element
31 substrate
32 pedestal
33 ribbon
34 electrode
35 mirror surface
36 axis assuming position
40 spatial light modulator (SLM)
41 pixel element
42 pixel element
43 light source
44 incidence angle α
45 reflection β
46 incident light beam
47 reflection
48 direction
49 plane normal
60 spatial light modulator (SLM)
61 ribbon (diffractive element)
62 prism
63 reflective surface
64 beam of light

5

65 beam

66 beam

67 lens

68 blocker

69 group of lenses

70 image plane

71 image

210 diffractive element

220 diffractive element

410 ribbon (diffracting element)

420 ribbon (diffracting element)

600 optical system

The invention claimed is:

1. A method for modulating light using a micro-electro-mechanical structure comprising:

providing a plurality of deformable mirror elements having an L-shaped cross section;

wherein each of said deformable mirror elements is comprised of a pedestal and an elongated ribbon attached to the pedestal on a long axis of the ribbon;

wherein each of said ribbons has a reflective surface;

directing a beam of light on said deformable mirror elements; and

flexing one or more reflective ribbons about one or more long axes of one or more reflective ribbons to vary a curvature of one or more reflective ribbons.

2. The method of claim 1 wherein said reflective surface has one or more reflective segments.

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3. The method of claim 1 wherein each of said reflective ribbons flexes independently.

4. The method of claim 1 wherein each of the pedestals is anchored to a substrate parallel to each adjacent pedestal.

5. The method of claim 1 further comprising: providing an activation device on each of said ribbons.

6. The method of claim 5 further comprising: activating said activation device to induce curvature in a pixel group of said ribbons.

7. The method of claim 5 further comprising: providing complimentary activation devices on a substrate that anchors the pedestal on each of said deformable mirror elements to induce curvature in said ribbons.

8. The method of claim 5 wherein said activation device is selected from a group comprising electrical, magnetic, or heating elements.

9. The method of claim 1 wherein the reflective surface is conductive.

10. The method of claim 1 wherein the reflective surface is matched to a wavelength of the light.

11. The method of claim 1 wherein the reflective surface is aluminum and the wavelength of the light is in the visible range.

12. The method of claim 1 wherein the reflective surface is gold and the wavelength of the light is in the infrared range.

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